

ADDITIONAL ULTRACOOL WHITE DWARFS FOUND IN THE SLOAN DIGITAL SKY SURVEY

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ABSTRACT

We identify seven new ultracool white dwarfs discovered in the Sloan Digital Sky Survey (SDSS). The SDSS photometry, spectra, and proper motions are presented, and additional *BVRi* data are given for these and other previously discovered ultracool white dwarfs. The observed colors span a remarkably wide range, qualitatively similar to colors predicted by models for very cool white dwarfs. One of the new stars (SDSS J1251+44) exhibits strong collision-induced absorption (CIA) in its spectra, while the spectra and colors of the other six are consistent with mild CIA. Another of the new discoveries (SDSS J2239+00A) is part of a binary system—its companion is also a cool white dwarf, and other data indicate that the companion exhibits an infrared flux deficiency, making this the first binary system composed of two CIA white dwarfs. A third discovery (SDSS J0310–00) has weak Balmer emission lines. The proper motions of all seven stars are consistent with membership in the disk or thick disk.

Subject headings: solar neighborhood — white dwarfs

1. INTRODUCTION

As white dwarfs cool below an effective temperature of roughly 4000 K, the density of gas in the photosphere increases to a point where models of the atmosphere must include effects not normally important in standard stellar models. Absorption by molecular hydrogen, referred to as collision-induced absorption (CIA), becomes dominant at near-infrared wavelengths in the high-density gas. It affects the radiative energy transport in atmospheres of brown dwarfs, but it can severely modify the emergent broadband colors of cool white dwarfs (Bergeron et al. 1995a; Saumon & Jacobson 1999; Hansen 1999; Gates et al. 2004). Calculations of CIA (Jørgensen et al. 2000; Borysow et al. 2001) to be used as an opacity source in stellar models have become more realistic, but further improvements can and are being made. Other opacity effects (Kowalski & Saumon 2006) and non-ideal-gas treatment (Kowalski 2006 and references therein) also become important, and challenge current models for both white dwarfs and cool brown dwarfs.

Because most stars evolve into white dwarfs, the cool white dwarfs found now in the solar neighborhood provide a record of star formation in the Galactic halo, the thick disk, and the early history of the thin disk. Utilizing white dwarfs to extract star formation histories requires separating these populations of white dwarfs; for example, Reid (2005) describes a procedure to accomplish this separation, but it is necessarily based on some simplifying, model-dependent assumptions such as the mass distribution of white dwarfs in each population. For applying white dwarfs to study the Galactic halo and thick disk and the age of the thin

disk, knowing the origin and evolution of the coolest white dwarfs is required.

Only recently have any white dwarfs been identified that exhibit CIA: these include LHS 1126 (Bergeron et al. 1994), WD 0346 (Hambly et al. 1997), LHS 3250 (Harris et al. 1999), LHS 1402 (Oppenheimer et al. 2001), SDSS J1337+00 (Harris et al. 2001a), five new SDSS discoveries (Gates et al. 2004), GD 392B (Farihi 2004), COMBO-17 J1146–01 (Wolf 2005), and the faintest white dwarfs detected in the globular cluster NGC 6397 (Richer et al. 2006; Hansen et al. 2007).¹¹ Several have been individual and serendipitous discoveries. However, the Sloan Digital Sky Survey (SDSS; York et al. 2000; Gunn et al. 1998, 2006; Stoughton et al. 2002) is suitable for systematically finding the coolest white dwarfs through its accurate broadband photometry (Fukugita et al. 1996; Hogg et al. 2001; Lupton et al. 2001; Smith et al. 2002; Ivezić et al. 2004; Tucker et al. 2006), spectroscopy of selected targets, and astrometry (Pier et al. 2003; Munn et al. 2004). The six very cool white dwarfs discovered in the SDSS thus far have contributed half of the known sample. These increased numbers help address both of the above goals of improving white dwarf models and understanding the evolution of white dwarfs, but much larger samples are still needed.

In this paper we present data for an additional seven “ultracool” white dwarfs discovered in the SDSS. The wavelength coverage of SDSS data ($\lambda < 1 \mu\text{m}$) allows discrimination of the coolest white dwarfs only when CIA is sufficiently strong to affect their optical colors and spectra. Therefore, mild CIA stars such as WD 0346 cannot be identified with SDSS data alone, and are not included as new discoveries in this paper. Following Gates et al. (2004), we use the term “ultracool” to refer to white dwarfs with CIA detectable at wavelengths shorter than $1 \mu\text{m}$.

2. OBSERVATIONS

The ultracool white dwarfs in this paper have been found in searches of SDSS spectra available to the SDSS Collaboration

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¹¹ In addition, there are some very cool white dwarfs that probably show CIA but require additional data to confirm their classification: LHS 2288 (Scholz et al. 2005), CE 51 (Ruiz & Bergeron 2001), the companion to PSR J0751+1807 (Bassa et al. 2006), and several candidates from SDSS (Kilic et al. 2006).

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TABLE 1
NEW ULTRACOOL WHITE DWARFS

Parameter	J0146+14	J0310-01	J1238+35	J1251+44	J1452+45	J1632+24 ^a	J2239+00
R.A. ^b	01 46 29.01	03 10 49.53	12 38 12.85	12 51 06.12	14 52 39.00	16 32 42.23	22 39 54.12
Decl. ^b	+14 04 38.2	-01 10 35.3	+35 02 49.1	+44 03 03.1	+45 22 38.3	+24 26 55.2	+00 18 47.3
Epoch ^b	1999.7818	2002.6779	2004.2905	2003.2310	2003.4059	2003.4693	2001.7870
μ (mas yr ⁻¹)	255	88	180	170	93	340	98
μ_α (mas yr ⁻¹)	252	-36	-130	-167	-54	-10	7
μ_δ (mas yr ⁻¹)	38	-80	-124	30	76	-340	98
u	21.19	22.37	24.74	21.43	21.55	21.33	21.46
g	19.97	20.93	21.73	20.18	20.06	19.60	20.15
r	19.38	20.18	20.30	20.39	19.39	18.72	19.52
i	19.26	19.87	19.86	20.69	19.31	18.51	19.49
z	19.70	19.99	20.32	20.90	19.38	18.47	20.09
H_g ^c	22.00	20.64	23.00	21.33	19.91	22.26	20.11
Distance (pc)	26-67	40-99	48-121	36-90	27-68	21-52	28-72
v_{tan} (km s ⁻¹)	32-80	17-42	41-103	29-73	12-30	33-84	13-33
MJD/plate/fiber ^d	53262/1899/493	53386/2068/054	53431/2020/417	53063/1373/176	53466/1675/014	53226/1573/635	53261/1901/400

^a SDSS J1632+24 previously found as LP386-28 (Luyten 1979) = WD1630+245 (McCook & Sion 1999).

^b Coordinates are given for equinox J2000.0 at the observed epoch. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

^c Reduced proper motion ($H_g = g + 5 \log \mu + 5$).

^d SDSS spectra: MJD of observation/plate number/fiber number.

through 2006. The data set is approximately coincident with the SDSS DR6 data release (Adelman-McCarthy et al. 2008), with spectroscopic data covering 7425 deg² of the sky; this paper increases the sky coverage by about 70% beyond that of the previous paper by Gates et al. (2004). The seven stars in this paper were targeted for spectroscopic observations under six different selection categories described in § 3 below.

Among the SDSS spectra of cool white dwarfs with featureless DC spectra, there are a number that we have classified as normal, not ultracool. The distinction is not always clear, because the SDSS spectra of faint stars ($g \sim 19$) have poor signal/noise at the red end from the difficult subtraction of the strong night sky emission, and because the z magnitudes have larger errors than the gri magnitudes. In this paper, we have relied primarily on the $i - z$ color, requiring it to be significantly bluer for the stars we classify as ultracool than for normal cool white dwarfs. Additional infrared observations are desirable to further study where stars lie in the transition region from normal cool white dwarfs, to white dwarfs with weak CIA detectable only in the infrared, to the ultracool stars described in this paper.

Data for the seven new ultracool white dwarfs are given in Table 1, and the SDSS spectra are shown in Figure 1. Positions and magnitudes are taken from the SDSS database. Proper motions, calculated as described by Munn et al. (2004) are included in Table 1. For two stars that are sufficiently bright and unblended to provide reliable matches with objects in the USNO-B catalog (Monet et al. 2003), proper motions are taken from the SDSS database. For five stars that are too faint or are confused in USNO-B, we calculated new proper motions using the Munn procedure, using the SDSS position plus those USNO-B plate positions that did appear reliable.

Additional photometry in the Johnson/Cousins $BVRI$ system has been obtained with the 40 inch (1.02 m) telescope of the US Naval Observatory in Flagstaff. These data were obtained in order to help confirm the unusual colors of some of these stars caused by CIA, and to enable comparisons with other stars not yet observed with SDSS filters. Observations were made on eight nights during 2005–2007 with a Tektronix CCD and standard filters. Magnitudes and colors were transformed to the stan-

dard system using Landolt (1992) standards. The results are given in Table 2.

Only one of these seven new ultracool white dwarfs shows strong CIA—in Figure 1, SDSS J1251+44 has a maximum in its flux density f_ν at 5000 Å, bluer than any other ultracool white dwarf. Its $B - V$ color of +0.28 is consistent with the very strong red and infrared absorption by CIA indicated by the SDSS colors. Its $griz$ and BVI colors are more like an A star or a quasar than a cool white dwarf, and create some doubt about its nature. However, the reduced proper motion given in Table 1 must be approximately correct,¹² and is much too large to allow classification as something other than a white dwarf. Furthermore, the lack of real features in the (admittedly noisy) spectrum is not consistent with a horizontal branch or blue straggler star. Some new type of warm white dwarf (perhaps magnetic?) might be possible, but the drop in flux at the blue end of the spectrum and the red $u - g$ color are unlike any known warm white dwarf. A few DZ white dwarfs with strong absorption by metals (Dufour et al. 2007) have spectra that are superficially similar, but always show calcium and/or magnesium features that are absent in SDSS J1251+44. Therefore, we prefer a “conventional” classification of a white dwarf with strong CIA.

The remaining six stars have mild CIA, as shown by their red colors and spectra. The weakest CIA occurs in SDSS J0310-01, where the $ugri$ colors are consistent with a normal cool white dwarf, and only the $i - z$ color of -0.12 reveals its ultracool nature. The result is that these seven white dwarfs have a surprisingly large range of colors: $g - r$ ranges from -0.21 to 1.43.

SDSS J2239+00 has a companion with a separation of 2.0". The companion star, SDSS J223954.07+001849.2, has $griz$ magnitudes of 21.00, 19.94, 19.60, and 19.43. (The u magnitude of 24.1 is too faint and noisy to be useful.) The pair is just visible

¹² By chance, SDSS J1251+44 lies on 14 POSS plates in the USNO pixel database. It is clearly detected on four plates, marginally visible on four plates, and not visible on six plates (all of the POSS-I E and POSS-II IV-N plates). The proper motion given in Table 1 is somewhat uncertain depending on whether the marginal detections are considered real and are included or omitted from the solution. Nevertheless, the definite detections on POSS-II plates taken between 1988 and 1997, plus the SDSS detection in 2003, show a clear westward motion.

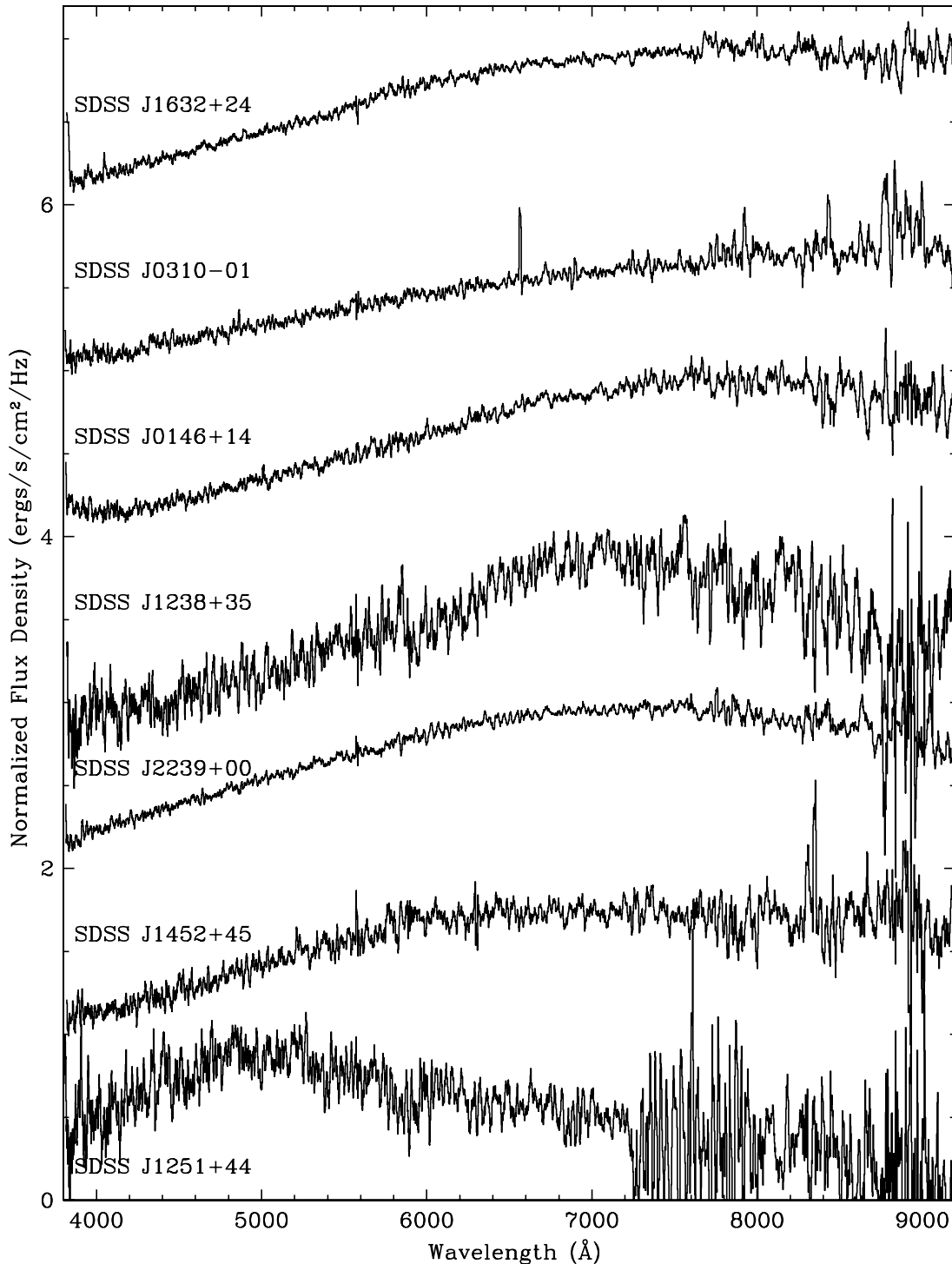


FIG. 1.—SDSS spectra for the seven new white dwarfs in this paper. Spectra have been smoothed by nine pixels to a resolution of 800, and are normalized and offset vertically by one unit for display. Compare with Fig. 2 of Gates et al. (2004) for SDSS spectra of previously observed cool white dwarfs.

on a UK Schmidt R plate taken in 1988, with the separation and orientation appearing unchanged between 1988 and the imaging done by SDSS in 2001 and at USNO in 2005. Therefore, the pair probably has common proper motion and is a physical binary. The separation is large enough that the spectrum in Figure 1 (taken with a 3'' fiber) should not have been significantly contaminated by the companion, and, indeed, the colors and spectrum appear to be mutually consistent. The companion is itself a cool white dwarf, as indicated by its colors and reduced proper motion. The *griz* colors given above and the *BVRI* colors in

Table 2 indicate that it is a normal cool white dwarf. The companion's red *i - z* color of +0.17 places it close to the red limit that is observed for cool white dwarfs, and shows that its optical colors have not yet begun to turn blue from CIA. However, Vidrih et al. (2007) have discovered from UKIDSS near-infrared photometry that the companion is deficient in *K* flux, indicating the onset of CIA. Therefore, this is a pair of cool white dwarfs, where weak CIA is affecting the companion's infrared flux and stronger CIA is affecting the optical spectrum and colors of SDSS J2239+00. It is the first such pair of CIA white dwarfs

TABLE 2
BVRI PHOTOMETRY

Star	V	$B - V$	$V - R$	$V - I$	N_{obs}
SDSS J0146+14.....	19.74 ± 0.07	...	0.58 ± 0.09	0.85 ± 0.09	1
SDSS J0854+35.....	19.80 ± 0.03	...	0.67 ± 0.04	1.15 ± 0.04	1
SDSS J0947+44A ^a	19.12 ± 0.02	0.76 ± 0.02	0.40 ± 0.02	0.45 ± 0.03	2
SDSS J0947+44B ^b	19.09 ± 0.02	0.93 ± 0.03	0.52 ± 0.02	1.04 ± 0.02	2
SDSS J1001+39.....	19.68 ± 0.02	0.74 ± 0.04	0.22 ± 0.03	-0.08 ± 0.05	2
SDSS J1220+09.....	19.67 ± 0.03	1.23 ± 0.07	0.48 ± 0.04	0.43 ± 0.09	3
SDSS J1251+44.....	20.18 ± 0.03	0.28 ± 0.05	-0.15 ± 0.05	-0.20 ± 0.07	4
SDSS J1403+45.....	18.81 ± 0.02	0.56 ± 0.04	-0.15 ± 0.03	-0.54 ± 0.05	2
SDSS J1452+45.....	19.68 ± 0.03	0.77 ± 0.08	...	0.60 ± 0.08	1
SDSS J1632+24.....	19.09 ± 0.03	1.04 ± 0.04	0.51 ± 0.03	0.95 ± 0.03	2
SDSS J2239+00A ^a	19.78 ± 0.04	0.70 ± 0.07	0.38 ± 0.07	0.61 ± 0.05	2
SDSS J2239+00B ^b	20.23 ± 0.05	1.11 ± 0.13	0.75 ± 0.07	1.18 ± 0.06	2

^a SDSS J0947+44A and J2239+00A are the ultracool dwarfs.

^b SDSS J0947+44B and J2239+00B are the common-proper-motion companion white dwarfs.

identified. Vidrih et al. derive a distance of 55 pc, consistent with the distance that we estimate below (Table 1) for the ultracool star.

3. DISCUSSION

Color-color plots are shown in Figure 2 for all 15 ultracool white dwarfs observed in SDSS; these are the seven new stars in this paper, the seven previous stars from Gates et al. (2004) and Harris et al. (2001a), and the one previous star from Wolf (2005). (This last star was present in the SDSS photometric database, but was not designated as an SDSS spectroscopic target because of its faint magnitude.) The stars have been arbitrarily divided into two groups, one group showing strong CIA in the spectra and colors (Fig. 3, *filled circles*) and a peak in the flux density f_ν shortward of 7000 Å, and the other showing more mild CIA and a peak in f_ν longward of 7000 Å. This division is not meant to imply that the groups are distinct, because there is probably a continuous distribution of CIA strengths. The two groups and symbols only help to interpret the figures by highlighting stars which are near the turnaround in color and stars which have cooled sufficiently (for their individual atmospheric hydrogen/helium abundances) to be well beyond the turnaround in color.

The new stars in this paper have filled in much of the gap in colors between the previous ultracool stars and the warmer cool white dwarfs that do not yet show CIA (Fig. 2, *dots*). The large variety of colors seen in Figure 2 probably is caused in part by a range of hydrogen/helium abundance ratios. Colors of models from Bergeron with two abundance ratios are shown in Figure 2. More recent models of pure hydrogen atmospheres that include additional opacity from the far red wing of the Ly α line (Kowalski & Saumon 2006) are also shown, and extend the range of model colors further to the red. It can be seen that the three models match the range of colors at which stars develop mild CIA and turn off from the sequence of normal cool white dwarfs. However, these models only qualitatively reproduce the range of colors for stronger CIA. A range of stellar masses, and corresponding surface gravities, also may be a contributing factor. Obviously, improved models are needed before they can be applied to this full set of stars and be expected to yield quantitative conclusions about temperature, abundance, and age.

The stars at the faint end of the white dwarf sequence in NGC 6397 (Hansen et al. 2007) appear to have colors similar to the mild CIA stars found in this paper. In NGC 6397, the faintest white dwarfs have a range in F606W–F814W of 0.4, corresponding to a range in $V - I$ of 0.5 or a range in $g - i$ of 0.6.

Aside from SDSS J1238+35, which is somewhat redder, this is exactly the range in $g - i$ seen in Figure 2 for the mild CIA stars. However, the masses, ages, and origin of the stars in this paper may be quite different from those in NGC 6397, as is discussed next.

The diagram of reduced proper motion in the g filter [$H_g = g + 5 \log \mu + 5$] is shown in Figure 3. The star with the largest value of H_g is SDSS J1220+09, with $H_g = 24$, and was noted by Gates et al. (2004) as being the best candidate for an old halo white dwarf. This situation has not changed—the other stars, including the new ones reported in this paper, have small enough proper motions that they are likely to have a disk (or perhaps thick disk) motion and origin. In Table 2 we include estimates of the distances and corresponding tangential velocities for each of the new ultracool white dwarfs based on assuming a wide range for the absolute magnitude ($M_V = 16.5 \pm 1.0$), following Salim et al. (2004) and Gates et al. (2004). Parallax measurements are essential for reducing the uncertainties in these estimates and for understanding the systematic properties (masses and disk/halo origins) of these stars; observations are in progress for measuring the parallaxes of several of these stars with USNO and MDM telescopes.

The spectrum of SDSS J0310–01 exhibits narrow H α emission (and probably H β) which suggests the presence of an unseen companion. Additional data at optical and/or IR wavelengths are needed to confirm this possibility and determine the nature of the companion, and will be reported in a future publication. Judging from Figure 2 of Dahn et al. (2002), which gives M_I versus spectral type, an L0 companion would contribute $M_I \sim 15$ –15.5, comparable to the likely absolute I mag of the white dwarf; this limit suggests that the companion should be at least early L. Admittedly, a rising contribution from the companion could be partially canceled by the CIA decline the white dwarf's energy distribution might have. Since such objects are generally not chromospherically active, and there is no significant ultraviolet radiation field, the narrow H α emission suggests the possibility of a close binary with rapid rotation perhaps synchronous with the orbital period. We have examined the individual exposures (13 exposures for this star) used in the SDSS spectrum in Figure 1, but they are noisy enough to mask any changes in the emission that might be occurring. Observations to search for periodic radial velocity variations should be obtained.

It is premature to add these new ultracool white dwarfs to any analysis of the space density and luminosity function of white dwarfs for two reasons: we do not yet have models to fit the spectra adequately to give accurate temperatures and H/He abundances,

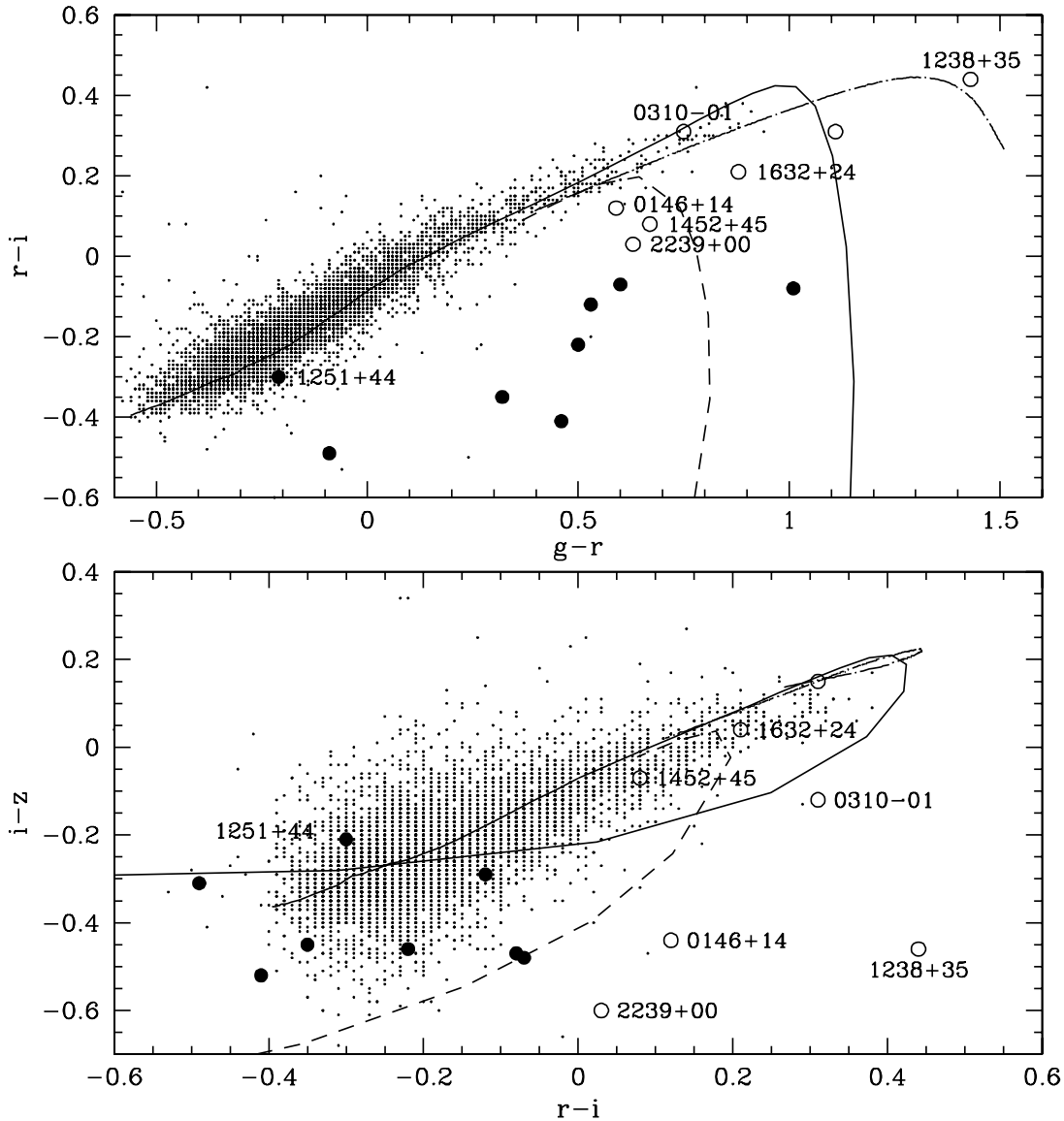


FIG. 2.—Color-color plots for ultracool white dwarfs in SDSS colors. Ultracool white dwarfs observed by SDSS are shown as filled circles for strong-CIA stars and open circles for mild-CIA stars. New stars identified in this paper are labeled. The proper-motion-selected white dwarfs used for the luminosity function by Harris et al. (2006) are shown as dots for comparison. The curves show models for white dwarfs with $\log g = 8$ with atmospheres of pure hydrogen (Bergeron et al. 1995b; solid line), pure hydrogen (Kowalski & Saumon 2006; dot-dashed line), and He/H = 10^5 (Bergeron & Leggett 2002; short-dashed line).

and we do not yet have distances to get luminosities, masses, and ages. Nevertheless, we can make a few comments about the effects these new stars might have on our understanding of the WDLF. First, only one of these stars (SDSS J1632+24) is bright enough to be discovered using Palomar Sky Survey plates, and its proper motion is too small to enter into the sample used for the WDLF by Liebert et al. (1988), or into the expanded sample with a lower proper motion limit being used by Harris et al. (2001b). Second, all of these new stars would have been detected in the deeper white dwarf sample by Knox et al. (1999) and contribute to their LF. However, their search covered only 25 deg², compared to the 7425 deg² in the SDSS DR6 area. Therefore, even if the SDSS spectroscopic sample is incomplete by a substantial factor for these stars with mild CIA, it is unlikely that even one such star is actually present in their sample. Third, none of these stars have $g < 19.5$, so none would have entered the sample used by Harris et al. (2006) to measure the WDLF with SDSS imaging data. Fourth, the one binary among these stars is too faint to be discovered on Sky Survey plates, so would not enter the sample

of binaries used for the WDLF by Oswalt et al. (1996). Fifth, only one of these stars (SDSS J1632+24) has a proper motion large enough to enter the sample of halo WD candidates found by Oppenheimer et al. (2001), and their analysis would have assigned it a distance of ~ 50 pc and $V_{\text{tan}} \sim 80$ km s⁻¹, so it would have been classified a disk star.

These comparisons suggest that none of the determinations of the WDLF up to now are affected by ultracool white dwarfs of the type found in this paper. In order to measure the LF that *does* include them, it is necessary to go to fainter magnitudes and/or larger areas of sky in order to sample a larger volume of space. One example is the 90-Prime survey (Liebert et al. 2007), a proper-motion follow-up to SDSS that is reaching about 2 mag fainter than the photographic surveys and will take advantage of the deep limiting magnitude of SDSS. A second example that may help determine the density of ultracool white dwarfs is the Sloan Extension for Galactic Understanding and Exploration (SEGUE), one of three surveys that comprise the second phase of SDSS. Of the seven new discoveries reported in this

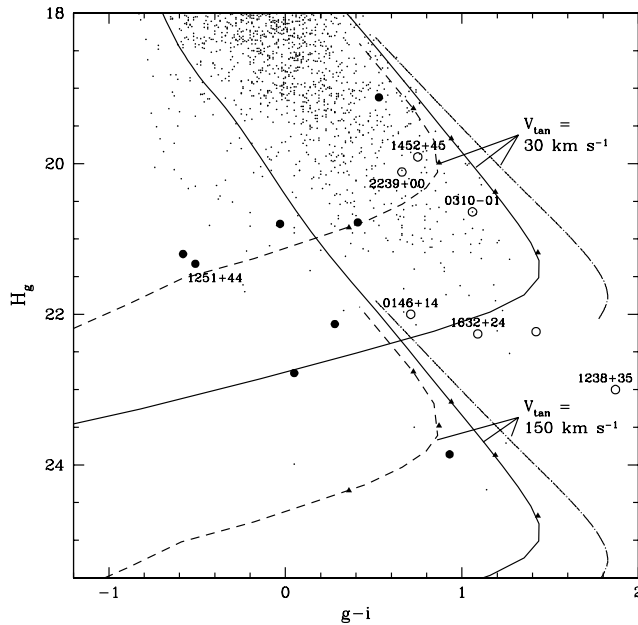


FIG. 3.— Reduced proper motion for ultracool white dwarfs observed by SDSS. The symbols and curves are the same as in Fig. 2. The model curves are plotted for two different assumed values of the tangential velocity, again assuming $\log g = 8$. On each curve showing Bergeron models (solid line for hydrogen, short-dashed line for mixed composition), three triangles indicate ages of 6, 8, and 10 Gyr (top to bottom).

paper, four were targeted for spectra as part of the SDSS main survey and three were targeted for spectra taken for SEGUE.¹³

¹³ SDSS J1238+35 was targeted by the QSO target selection category, SDSS J1251+44 by SERENDIPITY-DISTANT, and SDSS J1452+45 and SDSS J1632+24 by STAR_WHITE-DWARF (see Gates et al. 2004; Stoughton et al. 2002; Richards et al. 2002). SDSS J0310-01 and SDSS J2239+00 were targeted as cool white dwarf candidates by SEGUE, and SDSS J0146+14 was found serendipitously in early SEGUE spectra through preliminary target selection for red dwarfs.

SEGUE includes a target selection algorithm based on proper motion that is designed to include cool white dwarfs of all types, and should allow a complete sample to be identified of these ultracool white dwarfs with mild CIA. The SEGUE survey ultimately will cover 3500 deg² in imaging, and obtain spectra of stars along 200 lines of sight. Ten spectroscopic fibers per plate pair are being assigned to cool white dwarf candidates, for a total of roughly 2000 spectra. The density of 0.0014 deg⁻² stars with strong CIA with $i < 20.2$ (Gates et al. 2004) indicates that only two strong-CIA stars will be found in SEGUE, and probably two–four additional weak-CIA stars. However, the true density may be higher (Wolf 2005). Following this work, the PanSTARRS survey, and ultimately LSST, have the potential to greatly improve the complete samples that are needed for the WDLF.

P. Bergeron, P. Kowalski, and D. Saumon kindly calculated and made available SDSS colors of their model atmospheres. This research has made use of the USNOFS Image and Catalogue Archive operated by the United States Naval Observatory, Flagstaff Station (<http://www.nofs.navy.mil/data/fchpix>).

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